Measurement of the energy density as a function of pseudorapidity in proton–proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

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Measurement of the energy density as a function of pseudorapidity in proton–proton collisions at $\sqrt{s} = 13$ TeV

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Abstract A measurement of the energy density in proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV is presented. The data have been recorded with the CMS experiment at the LHC during low luminosity operations in 2015. The energy density is studied as a function of pseudorapidity in the ranges $-6.6 < \eta < -5.2$ and $3.15 < |\eta| < 5.20$. The results are compared with the predictions of several models. All the models considered suggest a different shape of the pseudorapidity dependence compared to that observed in the data. A comparison with LHC proton–proton collision data at $\sqrt{s} = 0.9$ and 7 TeV confirms the compatibility of the data with the hypothesis of limiting fragmentation.

1 Introduction

In the framework of quantum chromodynamics (QCD), inelastic proton–proton collisions are described by a combination of hard and soft exchanges between the constituents of the protons. Hard collisions between one or multiple pairs of partons are complemented by soft parton scattering from Multiple Parton Interactions (MPI) [1–4], parton shower effects including initial- and final-state radiation, which, along with projectile fragmentation, constitute the *underlying event* (cf. Ref. [5]). At the CERN LHC these effects can be studied at the highest possible centre-of-mass energies covering a very large angular phase space. The measurement of the average energy per proton–proton collision in different pseudorapidity (η) regions probes our general understanding of QCD multiparticle production. Moreover, because of the extended calorimetric instrumentation of the CMS experiment beyond $|\eta| > 3$, covering the full range from -6.6 to $+5.2$ in pseudorapidity, smaller scattering angles may be accessed compared to other measurements.

In this paper, a measurement of the energy density in proton–proton collisions at the centre-of-mass energy $\sqrt{s} =$ 13 TeV within the pseudorapidity ranges $-6.6 < \eta < -5.2$ and $3.15 < |\eta| < 5.20$ is presented. This measurement extends the $\sqrt{s}$ and pseudorapidity range covered by previous results from the CMS [6], ATLAS [7], and LHCb [8] Collaborations. The average energy density per collision is defined as

$$\frac{\mathrm{d}E}{\mathrm{d}\eta} = \frac{1}{N_{\mathrm{coll}}} \sum_i E_i \frac{c(\eta)}{\Delta\eta}, \tag{1}$$

where $\sum_i E_i$ is the summed energy measurements of all calorimeter towers i within a bin of pseudorapidity having a width $\Delta\eta$, $c(\eta)$ is the η-dependent conversion factor from the calorimeter measurements to a stable-particle level energy, and N_{coll} is the number of selected proton–proton collisions corrected for the contributions from noise and simultaneous pp collisions occurring in the same event (pileup). By *event* we refer to the data of one single LHC bunch crossing. To investigate various aspects of MPIs in high-energy proton–proton collisions the measurement is performed for several different categories of collision, each category defined by a specific event selection.

Moreover, the data collected at $\sqrt{s} = 13$ TeV are analysed together with data collected at 0.9 and 7 TeV [6]. This is interesting since projectile fragmentation can then be studied in the regions close to the beam rapidity, $y_{\mathrm{beam}} = \mathrm{acosh}(\sqrt{s}/2m_{\mathrm{p}})$, where m_{p} is the mass of the projectile particle, i.e. a proton in the present case. At $\sqrt{s} = 13$ TeV, $y_{\mathrm{beam}} \approx 9.5$, while at $\sqrt{s} = 0.9$ TeV it is just ≈ 6.8. Thus, the detectors of CMS, although located at fixed η, cover a very wide range in $\eta' = \eta - y_{\mathrm{beam}}$ when data recorded at different centre-of-mass energies are combined. The hypothesis of limiting fragmentation [9] suggests that particle production reveals longitudinal scaling, i.e. the dependence of very forward particle production on the centre-of-mass energy vanishes in the region $\eta' \approx 0$ [10]. In this paper, the hypothesis of limiting fragmentation is tested in collisions at $\sqrt{s}$ from 0.9 to 13 TeV.

Measurements of the energy density at collider energies are an important reference necessary for extrapolating to even higher centre-of-mass energies. The results reported here

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provide valuable input for the tuning of Monte Carlo models used to describe the highest energy hadronic interactions needed for the interpretation of cosmic ray measurements [11,12].

2 The CMS detector

At the heart of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a strong magnetic field of 3.8 T. The data used for this paper were taken in June 2015 during a period without magnetic field. Within the CMS magnet volume are an inner silicon pixel and strip tracker that measure charged particles in the range $|\eta| < 2.5$, a homogeneous lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. The corresponding endcap detectors instrument the pseudorapidity range up to $|\eta| \lesssim 3$ with tracking and calorimetry. Forward Cherenkov calorimeters extend the coverage beyond $|\eta| \gtrsim 3$. Muons are measured in gas-ionization detectors embedded in the steel return yoke.

The hadron forward (HF) calorimeters cover the region $2.9 < |\eta| < 5.2$ and consist of 2×432 readout towers, each containing a long and a short quartz fiber embedded within a steel absorber running parallel to the beam. The long fibers run the entire depth of the HF calorimeter (165 cm, or approximately 10 interaction length), while the short fibers start at a depth of 22 cm from the front of the detector. The response of each tower is determined from the sum of signal in the corresponding long and short fiber. There are 13 rings of towers in $|\eta|$, each with a size of $\Delta\eta \simeq 0.175$, except for the lowest and highest $|\eta|$ rings, which have a size $\Delta\eta \simeq 0.11$ and $\Delta\eta \simeq 0.30$, respectively. The azimuthal segmentation of all towers is $10°$, except for the one at highest $|\eta|$, which has $\Delta\varphi = 20°$.

The very forward angles on one side of CMS ($-6.6 < \eta < -5.2$) are covered by the CASTOR calorimeter. It has 16 azimuthal towers, each built from 14 longitudinal modules. The 2 front modules form the electromagnetic section, and the 12 rear modules form the hadronic section. The calorimeter is made of stacks of tungsten and quartz plates, read out by PMTs, in two half-cylindrical mechanical structures, and is placed around the beam pipe at a distance of − 14.4 m away from the nominal interaction point. The overall longitudinal depth of both CASTOR and HF corresponds to 10 hadronic interaction lengths. The CASTOR calorimeter is only operated during periods of low LHC luminosity ($\mathcal{L}_{\text{inst}} < 10^{30}\,\text{cm}^{-2}\,\text{s}^{-1}$) since it cannot distinguish the secondaries from simultaneous pileup collisions.

The present analysis is restricted to the range of pseudorapidity covered by the HF and CASTOR calorimeters, excluding the two lowest $|\eta|$ segments of the HF calorimeters because they are partially located in the shadow of the endcap calorimeters. This corresponds to a combined pseudorapidity range of $3.15 < |\eta| < 5.2$ and $-6.6 < \eta < -5.2$. The analysis is performed using a data sample corresponding to an integrated luminosity of $0.06\,\text{nb}^{-1}$ recorded with an average number of proton–proton interactions per bunch crossing of about 0.05.

A more detailed description of the CMS detector can be found in Ref. [13].

3 Monte Carlo models

In this paper, various Monte Carlo event generators are used to correct the data from detector- to stable-particle level and to compare with the experimental results.

The PYTHIA8 [14] generator is a general purpose Monte Carlo package that builds most of its predictive power upon hard-scattering matrix elements calculated in perturbative QCD and parton showering according to the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) [15–23] equations. The string fragmentation model [24] is used for hadronization. The free parameters of the simulations can be adjusted to describe measurements at different centre-of-mass energies, resulting in the production of different so-called *tunes* of the model [25].

In this analysis, PYTHIA8 (version 8.212) is used together with the CUETP8M1 [25], CUETP8S1 [25], and MONASH 2013 [26] tunes, as well as with the MBR model [27] combined with the 4C [28] and CUETP8M1 tunes. In the CUETP8M1 and CUETP8S1 tunes, which are based on the MONASH 2013 and 4C tunes, the parameters are adjusted to describe underlying event measurements from the Fermilab Tevatron and the LHC. The tunes are constructed using different parton distribution function sets (NNPDF2.3LO [29]) and CTEQ6L1 [30], respectively).

The EPOS- LHC [31] and QGSJETII.04 [32] generators are commonly used to describe extensive air showers in the atmosphere initiated by cosmic ray particles, where soft physics is of primary importance. A combination of Gribov–Regge multiple scattering [33], perturbative QCD, and string fragmentation are the cornerstones of both models. While QGSJETII.04 includes a small number of fundamental parameters, the phenomenology implemented in EPOS- LHC offers more opportunities for tuning. In EPOS- LHC a hydrodynamic, or collective, component is included in a parametrised form [31].

The collisions simulated with the MONASH and MBR tunes of PYTHIA8, and the EPOS- LHC and QGSJETII.04 event generators, have been processed with a detailed simulation of the full CMS detector based on GEANT4 [34] and reconstructed using the same software sequence that is used for recorded collision events. These four models are used to correct for detector effects.

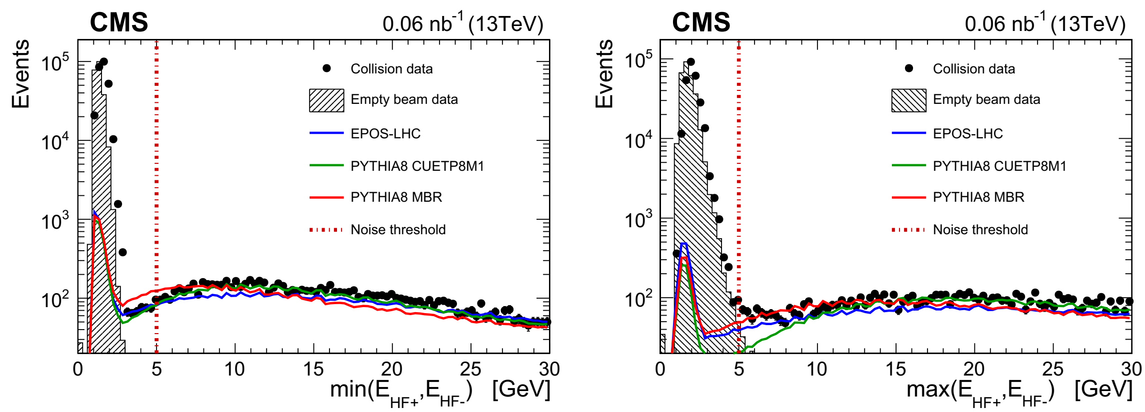

Fig. 1 Distribution of the absolute number of events as a function of the highest energy tower, $E_{\mathrm{HF+}}$ and $E_{\mathrm{HF-}}$, in the HF+ and HF− calorimeters. The left panel shows the smaller of the two HF calorimeter energies, $\min(E_{\mathrm{HF-}}, E_{\mathrm{HF+}})$, whereas the right panel shows the higher of the two energies, $\max(E_{\mathrm{HF-}}, E_{\mathrm{HF+}})$. The lines represent the simulations, while the markers represent the data. The measured detector noise distributions are shown as shaded areas

4 Event selection

Events are selected online in an unbiased way by triggering the data acquisition system with the Beam Pick-up-Timing for the eXperiments (BPTX) devices [35]. Three different categories of inelastic collisions are defined offline: an *inclusive inelastic* (INEL) selection to be as inclusive as possible, a *non-single-diffractive-enhanced* (NSD-enhanced) selection, where single diffractive dissociation contributions are suppressed, and a *single-diffractive-enhanced* (SD-enhanced) selection enriched in single diffractive dissociation collisions. These selections are achieved by requiring an energy deposit in the HF calorimeters above noise level either on at least one side (for the INEL category) or on both sides (for the NSD-enhanced category), with respect to the nominal interaction point of CMS. The SD-enhanced selection is defined by requiring activity in one of the calorimeters on exactly one side, with a veto condition being applied to the other side.

Energy deposition in the HF calorimeters is characterised by the calorimeter tower with the highest energy in the negative (positive) pseudorapidity region, $E_{\mathrm{HF-}}$ ($E_{\mathrm{HF+}}$), considering all towers, except those belonging to the two rings closest to the endcap (i.e. at smallest $|\eta|$). The energy thresholds for event selection are determined from a study of events without beam and are optimised to effectively reduce the contribution from detector noise, while still allowing a high selection efficiency. In Fig. 1, the measured distributions for $E_{\mathrm{HF-}}$ and $E_{\mathrm{HF+}}$ from collision data are shown together with the noise distributions obtained from data without the presence of LHC beams. This is achieved at the trigger level by requiring prescaled triggers where the two BPTX detectors are silent. In Fig. 1 simulated events are also shown. Events are selected for the INEL class if $\max(E_{\mathrm{HF-}}, E_{\mathrm{HF+}}) > E_{\mathrm{threshold}}$, and for the NSD-enhanced class if $\min(E_{\mathrm{HF-}}, E_{\mathrm{HF+}}) > E_{\mathrm{threshold}}$. An energy threshold of $E_{\mathrm{threshold}} = 5\,\mathrm{GeV}$ is found to be optimal to suppress the noise contribution in both event classes for simulated and measured events. For the NSD-enhanced category, the threshold could in principle be lowered down to about 3 GeV without increasing the noise contribution, but for consistency a unified threshold of 5 GeV is used for all event classes. The data were recorded at low luminosity with an interaction probability of about 5%. Most non-empty events contain a single proton–proton collision. A small fraction also has two or more interactions. In contrast, the simulation was done without pileup, i.e., each simulated event contains exactly one proton–proton collision. The detector noise distribution as measured from empty-beam data are also overlaid as shaded areas.

In simulated collisions particle four-momenta are used to build sums of energies. At the stable-particle level (i.e. for particles with proper decay length $c\tau > 1\,\mathrm{cm}$), simulated collisions are selected to be in the inclusive inelastic category if $\xi = \max(\xi_{\mathrm{X}}, \xi_{\mathrm{Y}}) > 10^{-6}$, where

$$\xi_{\mathrm{X}} = \frac{M_{\mathrm{X}}^2}{s}, \qquad \xi_{\mathrm{Y}} = \frac{M_{\mathrm{Y}}^2}{s}, \tag{2}$$

and M_{X} and M_{Y} are the invariant masses of the particle systems on the negative and positive side of the largest rapidity gap in the collision, respectively. This particular criterion for stable-particle level is identical within a few percent with the INEL detector level selection [36].

The NSD-enhanced collisions are selected at the stable-particle level with a requirement of at least one stable particle (either charged or neutral) within the pseudorapidity acceptance of the HF calorimeters $3.15 < |\eta| < 5.2$ on both sides of the interaction point.

The SD-enhanced collision at the stable-particle level are defined by the presence of at least one stable particle with energy $E > 5\,\mathrm{GeV}$ within the pseudorapidity range $3.15 <$

Table 1 Summary of the event selections used for the different event categories in data at the detector level and in simulations at the stable-particle level

Class	Detector level	Stable-particle level
INEL	$E_{\mathrm{HF}+} > 5\,\mathrm{GeV}$ or $E_{\mathrm{HF}-} > 5\,\mathrm{GeV}$	$\xi > 10^{-6}$
NSD-enhanced	$E_{\mathrm{HF}+} > 5\,\mathrm{GeV}$ and $E_{\mathrm{HF}-} > 5\,\mathrm{GeV}$	At least one stable particle with $E > 5\,\mathrm{GeV}$ in $-5.20 < \eta < -3.15$ and $3.15 < \eta < 5.20$
SD-enhanced	$E_{\mathrm{HF}+} > 5\,\mathrm{GeV}$ and $E_{\mathrm{HF}-} < 5\,\mathrm{GeV}$ or $E_{\mathrm{HF}+} < 5\,\mathrm{GeV}$ and $E_{\mathrm{HF}-} > 5\,\mathrm{GeV}$	At least one stable particle with $E > 5\,\mathrm{GeV}$ in $3.15 < \lvert\eta\rvert < 5.20$ on one side, vetoing particles with $E > 5\,\mathrm{GeV}$ on the other side
Limiting fragmentation study	$E_{\mathrm{HF}+} > 4\,\mathrm{GeV}$ and $E_{\mathrm{HF}-} > 4\,\mathrm{GeV}$	One stable particle in $-4.4 < \eta < -3.9$ and $3.9 < \eta < 4.4$

$\lvert\eta\rvert < 5.2$ on one side, whereas the other side must be devoid of particles with energy $E > 5\,\mathrm{GeV}$.

The phase space definitions for the NSD-enhanced, INEL and SD-enhanced categories at the detector and stable-particle level are summarised in Table 1. The last row of the table indicates the event selection needed for the limiting fragmentation study. This is chosen to be identical to that used in previously published data [6] to allow a direct comparison of the results.

The energy density is measured with the HF and CASTOR calorimeters by summing up all the energy deposits in the calorimeter towers above noise threshold. The value of the threshold was determined by measuring the detector noise and beam backgrounds using empty-beam triggers (see Fig. 1 for HF results) and is chosen to be 5 GeV in HF and 2.5 GeV in CASTOR. The energy density measurement is performed as a function of $\lvert\eta\rvert$. In the range $3.15 < \lvert\eta\rvert < 5.2$ the corresponding measurements at positive and negative pseudorapidities in HF are averaged, while for $-6.6 < \eta < -5.2$ the energy in CASTOR is used. For the SD-enhanced measurement only the side on which the HF calorimeter is above noise level (thus, opposite to the forward rapidity gap) is used for the measurement.

5 Data analysis

The measurement of the energy density according to Eq. (1) requires the determination of the number of selected collisions N_{coll} and the energy sum, $\sum_i E_i$.

5.1 Collision counting, noise, and pileup

The number of selected events in the analysis, N_{sel}, is corrected to eliminate the residual contribution from detector noise to yield the corrected number of events, N_{corr}, containing only signal and no noise events. In the following a fundamental and comprehensive discussion of event counting is provided despite the fact that the final corrections are just on the percent level. With N_{ZB} and N_{EB} being the number of events collected with the unbiased and empty-beam triggers, respectively, and f_{ZB} and f_{EB} the corresponding fractions of offline-selected events, we can define the number of selected collision events $N_{\mathrm{sel}} = N_{\mathrm{ZB}} f_{\mathrm{ZB}}$, and the number of noise events in the same data sample $N_{\mathrm{noise}} = N_{\mathrm{ZB}} f_{\mathrm{EB}}$. The latter contains $N_{\mathrm{sig+noise}} = N_{\mathrm{corr}} f_{\mathrm{EB}}$ events that are selected because towers in the same event are above threshold due to signal and noise fluctuations. Thus, the corrected number of events containing collisions is

$$\begin{aligned} N_{\mathrm{corr}} &= N_{\mathrm{sel}} - N_{\mathrm{noise}} + N_{\mathrm{sig+noise}} \\ &= \frac{N_{\mathrm{ZB}}(f_{\mathrm{ZB}} - f_{\mathrm{EB}})}{1 - f_{\mathrm{EB}}} \\ &= N_{\mathrm{ZB}} f_{\mathrm{ZB}}\, p, \end{aligned} \tag{3}$$

where we define the purity as $p = (1 - f_{\mathrm{EB}}/f_{\mathrm{ZB}})/(1 - f_{\mathrm{EB}})$. The purity of the data used in this analysis is found to be above 99%. The noise contribution depends weakly on the event selection criteria.

The reconstructed number of collisions is also corrected for the effect of pileup. The number of proton–proton interactions per bunch crossing n follows a Poisson distribution with a mean value $\lambda\epsilon$, where ϵ is the probability for each collision to be observed. The probability to have no interaction is given by $\mathrm{e}^{-\lambda\epsilon} = 1 - N_{\mathrm{corr}}/N_{\mathrm{ZB}}$, which allows λ to be determined from inelastic events in data. Here we find $\lambda = -\ln(1 - f_{\mathrm{ZB}}\, p)/\epsilon = 0.055 \pm 0.001$, using the value of f_{ZB} determined from the INEL event selection, and ϵ from simulations (see also Table 2). The uncertainty is driven by the model dependence of ϵ of about 2%.

The number of visible collisions in N_{tot} bunch crossings is $N_{\mathrm{vis}} = N_{\mathrm{tot}} \sum_{n=0}^{\infty} n\, \mathrm{Pois}\,(n; \lambda\epsilon) = N_{\mathrm{tot}}\lambda\epsilon$. In the presence of pileup another important quantity is the probability for the observation of events with exactly n simultaneous collisions, $\epsilon_n = 1 - (1 - \epsilon)^n$. The number of actually observed events is then $N_{\mathrm{obs}} = N_{\mathrm{tot}} \sum_{n=0}^{\infty} \epsilon_n\, \mathrm{Pois}\,(n; \lambda)$. Using this result we can correct for pileup using the factor

Table 2 Selection factors and purities for various event selection categories. Only the first two parameters f_{EB} and f_{ZB} present actual measurements, from which the other quantities are derived as explained in the text. The probability ϵ to select a single collision is determined from simulations, and the value quoted here is the average value from all event generators, with a maximal model dependence of 2%. The rightmost column quantifies the combined correction due to noise and pileup. All statistical uncertainties are negligible

	f_{ZB}	f_{EB}	p	ϵ (MC)	f_{PU}	$p\ f_{\mathrm{PU}}$
INEL	0.0490	0.0005	0.9902	0.9051	1.0250	1.0149
HF+	0.0442	0.0003	0.9935	0.8224	1.0227	1.0161
HF−	0.0439	0.0002	0.9956	0.8232	1.0228	1.0183
NSD-enhanced	–	–	–	–	–	1.0044
SD-enhanced	–	–	–	–	–	0.9804

$$f_{\mathrm{PU}} = \frac{N_{\mathrm{vis}}}{N_{\mathrm{obs}}} = \epsilon\lambda \left(\sum_{n=0}^{\infty} \epsilon_n \,\mathrm{Pois}\,(n;\lambda) \right)^{-1} = \frac{\epsilon\lambda}{1-\mathrm{e}^{-\epsilon\lambda}}. \tag{4}$$

For the data analysis we use the corrected number of collisions

$$N_{\mathrm{coll}} = N_{\mathrm{ZB}}\, f_{ZB}\, p f_{\mathrm{PU}} = -N_{\mathrm{ZB}} \ln \frac{1-f_{\mathrm{ZB}}}{1-f_{\mathrm{EB}}} \tag{5}$$

for Eq. (1). The same expression can also be obtained by arguing that during no-beam data taking the average number of collisions per event is $\lambda_{\mathrm{EB}} = -\ln(1-f_{\mathrm{EB}})$ whereas during normal data taking it is $\lambda_{\mathrm{coll}}+\lambda_{\mathrm{EB}} = -\ln(1-f_{\mathrm{ZB}})$. After inserting into $N_{\mathrm{coll}} = N_{\mathrm{ZB}}\lambda_{\mathrm{coll}}$ this is identical to Eq. (5). In the final expression only f_{EB} and f_{ZB} are relevant, thus, the parameters p and f_{PU} are intermediate quantities highlighting the individual importance of noise and pileup corrections. It must also be highlighted that the efficiency ϵ does not enter the final result.

In general, the impact of pileup depends on the event selection procedure. In particular, an exclusivity criterion as used in the SD-enhanced category leads to fewer selected events in the presence of a larger number of simultaneous collisions. Using the corrected number of inelastic collisions, N_{INEL}, and the corrected number of collisions inclusively selected by the HF+, $N_{\mathrm{HF+}}$, or by the HF$_-$, $N_{\mathrm{HF-}}$, the number of SD-enhanced collisions is calculated from $N_{\mathrm{SD}} = 2N_{\mathrm{INEL}} - N_{\mathrm{HF-}} - N_{\mathrm{HF+}}$. For NSD-enhanced collisions this relation is $N_{\mathrm{NSD}} = N_{\mathrm{HF-}} + N_{\mathrm{HF+}} - N_{\mathrm{INEL}}$. The results from this collision counting procedure are summarised in Table 2. The combined corrections for each category are at the level of 1%. The value quoted for ϵ is the average obtained from the different event generators with a maximum discrepancy between the model predictions of about 2%. The maximum uncertainty of deriving $p\ f_{\mathrm{PU}}$ is less than $< 10^{-3}$.

5.2 Energy measurement

The measured response from the calorimeters is corrected to the stable-particle level to provide a well-defined event classification and energy quantification for comparisons to the model predictions. The corrections are applied explicitly for each range in pseudorapidity. There is no relevant migration or detector smearing in pseudorapidity; it is basically the characteristic response of the calorimeters as well as the event selection acceptance and inefficiency that are corrected. These corrections are determined with the PYTHIA8 tune MONASH 2013, PYTHIA8 tune 4C with MBR model, EPOS- LHC, and QGSJETII.04 simulated event samples. The corrections are evaluated from the ratio of the predictions at the stable-particle level to the predictions at the detector level for every $|\eta|$ bin. The final correction is the average of the four different simulated samples. The magnitude of the correction varies from 1.5 to around 2.5 depending on the value of $|\eta|$ and the selection criteria applied at the stable-particle level. The main contribution to the correction is related to the extrapolation of observed detector-level energy above the calorimeter noise threshold to the energy with no threshold applied at the stable-particle level.

6 Uncertainties

The energy scales for the HF and CASTOR calorimeters are known to within an accuracy of 10% [6] and 17% [37], respectively. These are the dominant sources of experimental uncertainty in this analysis.

The impact of the energy scale uncertainty on the measurement of the energy density is estimated by scaling the tower energies up and down by the energy scale uncertainties in the data while keeping the simulated correction factors constant. The resulting impact is 10% for HF and 17% for CASTOR as expected.

To assess the residual impact of detector noise on the event selection, the thresholds in the event selection at detector level are increased from 5 to 5.5 GeV for all INEL, NSD-enhanced, and SD-enhanced categories. This corresponds to an improved noise rejection at the expense of larger correction factors. The resulting uncertainties are about 0.7, 0.01,

Table 3 The uncertainties in the energy density measurement for the three event selection categories. The results depend slightly on the pseudorapidity

Source of uncertainty	INEL	NSD-enhanced	SD-enhanced
HF energy scale	10%	10%	10%
CASTOR energy scale	17%	17%	17%
Noise and pileup	$\approx 10^{-3}$	$\approx 10^{-3}$	$\approx 10^{-3}$
Event selection	0.7%	0.01%	5%
Energy threshold in calorimeter towers	1%	1%	1%
Model dependence	< 3.5%	< 3.5%	16–37%
Statistical	< 1%	< 1%	< 1%

and 5% for the INEL, NSD-enhanced, and SD-enhanced categories, respectively.

Furthermore, to study the impact of the energy threshold on the energy measurement, the threshold for the tower energy sum is increased by the energy scale uncertainty, which leads to uncertainties of 1% for all three categories.

The systematic uncertainty due to model dependence is estimated from the maximum variation of the correction factor values obtained using the event generators PYTHIA8 with MONASH and 4C+MBR tunes, EPOS- LHC, and QGSJETII.04. The resulting uncertainty is below 3.5% for the INEL and NSD-enhanced categories, while for the SD-enhanced category it varies from 16 to 37%, depending on η.

The statistical uncertainty is $< 1\%$, which is significantly smaller than the systematic uncertainties.

The individual contributions for each $|\eta|$ bin are assumed to contribute quadratically to the total systematic uncertainty since the contributions are not correlated within a bin; the systematic uncertainties are, however, highly correlated between different $|\eta|$ bins. All uncertainties are summarised in Table 3.

7 Results

The measured energy density, $\mathrm{d}E/\mathrm{d}\eta$, in the range $-6.6 < \eta < -5.2$ and $3.15 < |\eta| < 5.20$, corrected to the stable-particle level, is presented in Figs. 2 and 3.

A comparison of the measured average energy density to model predictions for the INEL selection is shown in Figs. 2 (upper) and 3 (upper). The gray band represents the total systematic uncertainty correlated across $|\eta|$ bins. The statistical uncertainties are <1% and are not shown. In the left panel the comparison of the distribution in data and simulation is shown, while in the right panel the ratio quantifies the agreement between them. While the cosmic ray models (EPOS- LHC and QGSJETII.04) and the PYTHIA8 MONASH tune describe the data well at $|\eta| < 4$ and in the CASTOR region, they overshoot the data around $|\eta| \approx 4.5$. This is most pronounced in QGSJETII.04. The PYTHIA8 CUET tunes describe the data slightly better, but have a tendency to undershoot the data towards $|\eta| < 3.5$. The band around PYTHIA8 CUETP8S1 in Fig. 3 indicates the typical uncertainties due to the tune parameters. The best description of the data is provided by the PYTHIA8 tune CUETP8S1. When MPIs are switched off in PYTHIA8 more than half of the measured energy is missing, with a slight dependence on η.

In Figs. 2 (middle) and 3 (middle) the energy density measurements are compared with predictions for the NSD-enhanced category. The differences between the model predictions are smaller compared with the INEL category. The EPOS- LHC and QGSJETII.04 hadronic event generators overshoot the measurement only at $|\eta| \approx 4.5$ and otherwise show a good description of the data. The PYTHIA8 tune CUETP8S1 at the upper limit of its uncertainties provides the best overall description of the data.

Figure 2 (lower) shows a comparison of the energy density measurements as a function of η for the SD-enhanced category to predictions from PYTHIA8 MONASH, EPOS- LHC, and QGSJETII.04. The comparison of the same data to the different PYTHIA8 tunes is shown in Fig. 3 (lower). For the SD-enhanced category the model spread becomes significantly larger. It is interesting that the EPOS- LHC and QGSJETII.04 models are both compatible with the data only at the very lower limit of the systematic uncertainties, while all PYTHIA8 tunes are consistent with the data within the uncertainties. Furthermore, the shape of all the model predictions is very similar and, in contrast to the INEL and NSD-enhanced data, consistent with the data. Finally, we observe that for the SD-enhanced category switching off MPIs in simulations has almost no impact on the model predictions. This is an indication that the influence of MPIs within the diffractive system is small, whereas MPIs between the colliding protons will quickly destroy the single-diffractive-enhanced signature. Thus, the SD-enhanced event selection is an effective way to minimise MPI effects.

For a detailed comparison to previously published energy density results at lower centre-of-mass energies [6], the event selection is adapted to match the one previously used at detector and stable-particle levels. The whole measurement is repeated for the NSD-enhanced category with the requirement of at least one charged particle on both sides of the interaction point in the pseudorapidity range $3.9 < |\eta| < 4.4$. This is combined with a reduced energy threshold of 4 GeV to ensure consistency. Finally, for all calculations the transverse

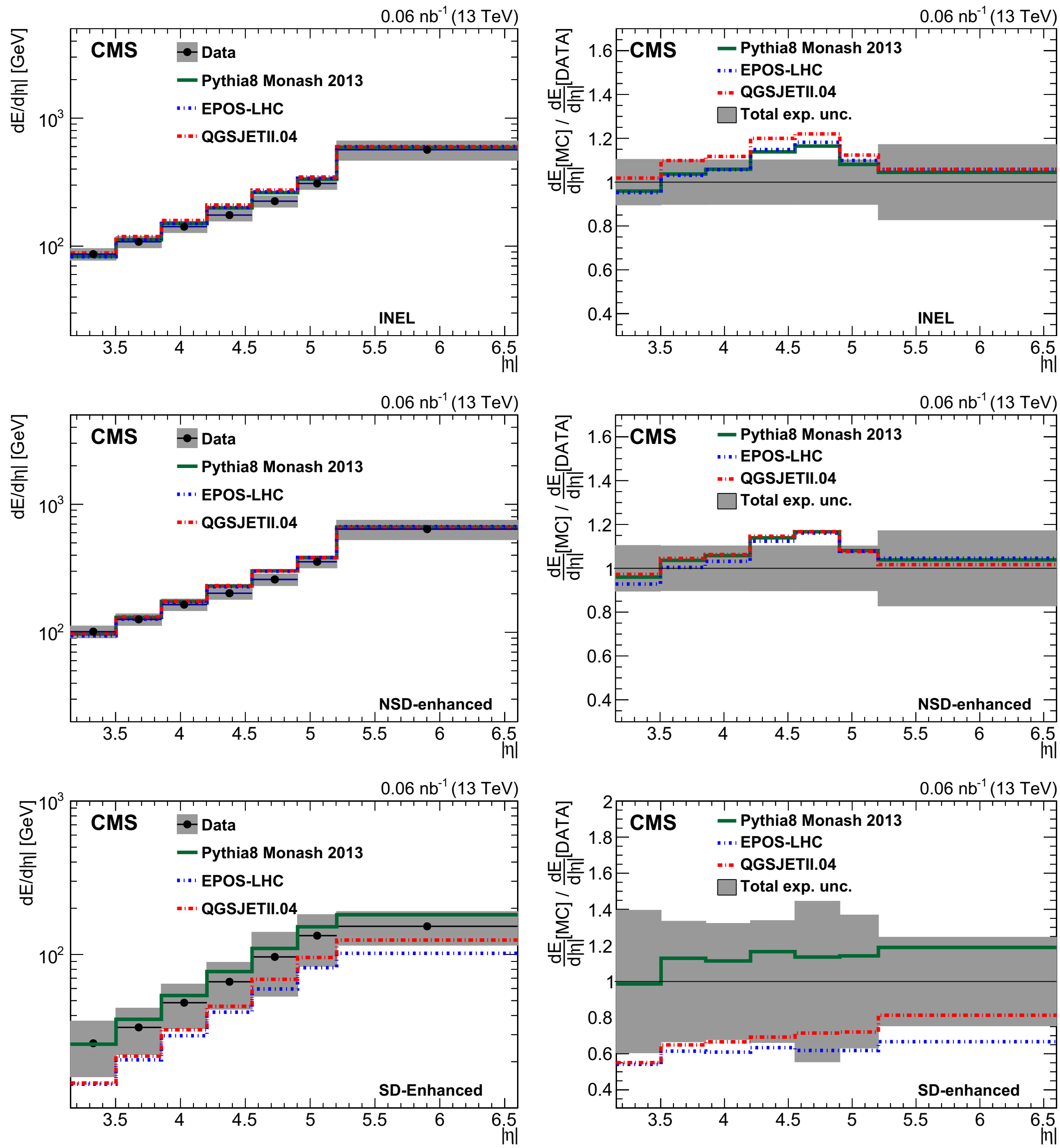

Fig. 2 Energy density at the stable-particle level for the INEL (upper row), NSD-enhanced (middle row), and SD-enhanced (lower row) categories compared to predictions from PYTHIA8 MONASH, EPOS- LHC, and QGSJETII.04. The gray band shows the total systematic uncertainty. The right panels show the ratio of model predictions to measured data

energy $E_T = E \cosh(\eta)$ per tower is used instead of just the tower energy E. In Fig. 4 the resulting corrected transverse energy density, $dE_T/d\eta'$, is compared to earlier published CMS data at lower $\sqrt{s}$ and to model predictions, as a function of the shifted pseudorapidity variable $\eta' = \eta - y_{beam}$. The analysis presented here uses the latest CMS detector description in the simulations, which includes an improved knowledge of the HF nonuniformity due to nonsensitive areas [38], that was not present in the original publication [6]. In order to facilitate the direct comparison of the current analysis with earlier results [6], corrections are applied to the published data that cause the results in the HF to be shifted in an η-dependent way; from about -2% at $|\eta| = 3$ to about -15% at $|\eta| = 5$, which is within the experimental uncertainties of these data.

A comparison of the model predictions and data at different $\sqrt{s}$ is shown in Fig. 4. Both the data and the model predictions are shifted by the beam rapidity to $\eta' = \eta - y_{beam}$. The data are consistent with longitudinal scaling within the experimental uncertainties. The observed behaviour is in agreement with the measurements of earlier experiments in proton–proton and heavy ion collisions (e.g. [38]). At $\eta' \approx 0$

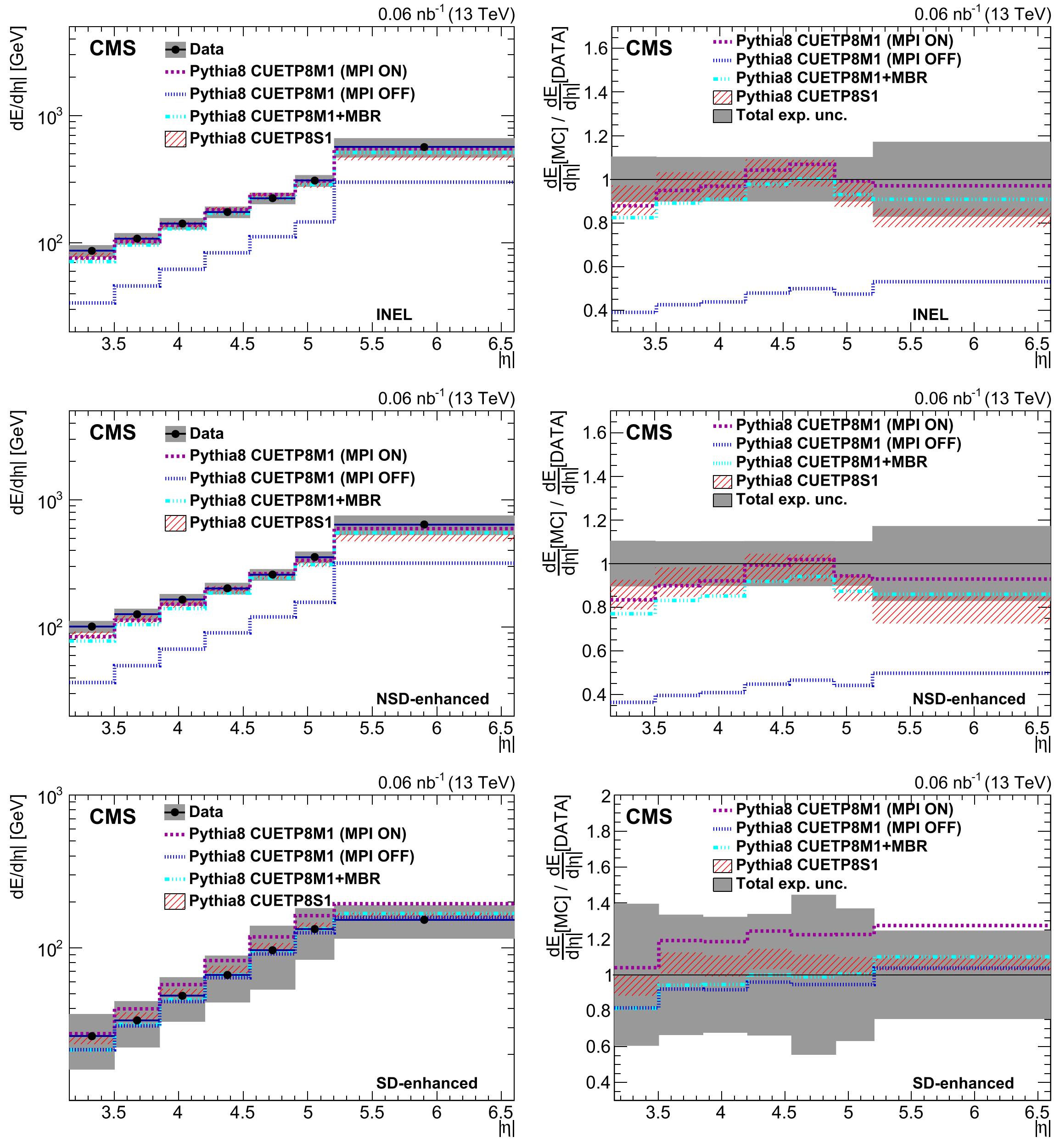

Fig. 3 Energy density at the stable-particle level for the INEL (upper row), NSD-enhanced (middle row), and SD-enhanced (lower row) categories compared to predictions from PYTHIA8 with the tunes CUETP8M1, CUETP8M1+MBR, and CUETP8S1. The gray band shows the total systematic uncertainty. The band around PYTHIA8 CUETP8S1 corresponds to the uncertainties of the tune parameters. The right panels show the ratio of model predictions to measured data

the transverse energy density does not depend on $\sqrt{s}$, which is in agreement with the hypothesis of limiting fragmentation.

8 Summary

The energy density, $\mathrm{d}E/\mathrm{d}\eta$, is measured in the pseudorapidity range $-6.6 < \eta < -5.2$ and $3.15 < |\eta| < 5.20$. Special low-luminosity data recorded by the CMS experiment during proton–proton collisions at the centre-of-mass energy $\sqrt{s} = 13\,\mathrm{TeV}$ are analysed for this purpose. The data are presented at the stable-particle level to allow a straightforward comparison to any theory prediction or model simulation. The measurements are compared to models tuned to describe high-energy hadronic interactions (PYTHIA8) and to the predictions of models used in cosmic ray physics (EPOS- LHC, QGSJETII.04) for inclusive inelastic (INEL), non-single-diffractive-enhanced (NSD-enhanced), and single-diffractive-enhanced (SD-enhanced) event selection categories.

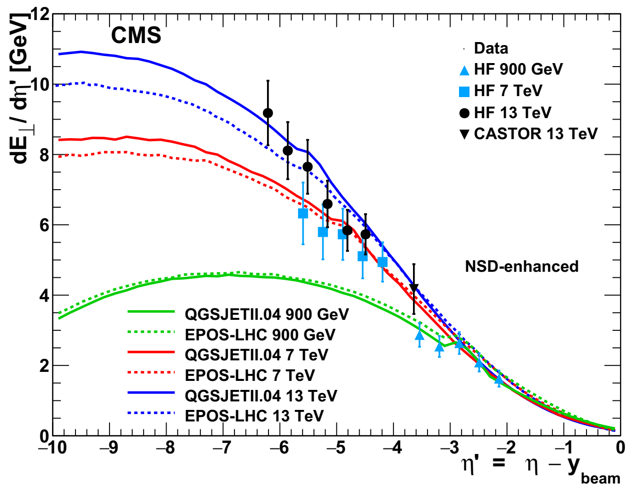

Fig. 4 A comparison of the measurements of the transverse energy density, $\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta'$, at $\sqrt{s} = 13$ TeV, as a function of shifted pseudorapidity, $\eta' = \eta - y_{\mathrm{beam}}$, to the predictions and to earlier proton–proton data [6] for an NSD-enhanced selected sample at several different centre-of-mass energies. The error bars indicate the total systematic uncertainties. The beam rapidities y_{beam} are about 9.5, 8.9, and 6.8 at $\sqrt{s}$ of 13, 7 and 0.9 TeV, respectively

It is shown that the INEL and NSD-enhanced categories are extremely sensitive to multi-parton interactions, while the SD-enhanced category is essentially unaffected. The shape of the measured η dependencies suggest a difference in the models compared to the data. However, the predictions of PYTHIA8 tune CUETP8S1 are in satisfactory agreement with all measurements when the experimental and tune uncertainties are combined. The EPOS- LHC and QGSJETII.04 models exhibit the largest differences when compared to the single-diffractive-enhanced results.

At high energies, the hypothesis of limiting fragmentation [9,10] assumes a longitudinal scaling behaviour in terms of shifted pseudorapidity $\eta' = \eta - y_{\mathrm{beam}}$ (where y_{beam} is the beam rapidity) and thus soft-particle production in the projectile fragmentation region, $\eta' \approx 0$, is predicted to be independent of the centre-of-mass energy. This is studied by measuring the transverse energy density $\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta$, with $E_{\mathrm{T}} = E\cosh(\eta)$, and comparing it to measurements performed in proton–proton collisions at different centre-of-mass energies. The predictions of the EPOS- LHC and QGSJETII.04 models nicely describe the combined data in the forward pseudorapidity range close to the projectile fragmentation region. The result supports the mechanism of limiting fragmentation. Since this predicts the independence of very forward particle production on the energy of the projectile particle, these data are very important for the modelling of ultra-high energy interactions that typically occur in cosmic ray collisions.

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31: Also at ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT, Bologna, Italy
32: Also at Università degli Studi di Siena, Siena, Italy
33: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
34: Also at Kyunghee University, Seoul, Korea
35: Also at Riga Technical University, Riga, Latvia
36: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
37: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
38: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
39: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
40: Also at Institute for Nuclear Research, Moscow, Russia
41: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
42: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
43: Also at University of Florida, Gainesville, USA
44: Also at P.N. Lebedev Physical Institute, Moscow, Russia
45: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
46: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia

47: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
48: Also at INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
49: Also at National and Kapodistrian University of Athens, Athens, Greece
50: Also at Universität Zürich, Zurich, Switzerland
51: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
52: Also at Adiyaman University, Adiyaman, Turkey
53: Also at Istanbul Aydin University, Istanbul, Turkey
54: Also at Mersin University, Mersin, Turkey
55: Also at Piri Reis University, Istanbul, Turkey
56: Also at Ozyegin University, Istanbul, Turkey
57: Also at Izmir Institute of Technology, Izmir, Turkey
58: Also at Marmara University, Istanbul, Turkey
59: Also at Kafkas University, Kars, Turkey
60: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
61: Also at Istanbul Bilgi University, Istanbul, Turkey
62: Also at Hacettepe University, Ankara, Turkey
63: Also at Rutherford Appleton Laboratory, Didcot, UK
64: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
65: Also at Monash University, Faculty of Science, Clayton, Australia
66: Also at Bethel University, St. Paul, USA
67: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
68: Also at Purdue University, West Lafayette, USA
69: Also at Beykent University, Istanbul, Turkey
70: Also at Bingol University, Bingol, Turkey
71: Also at Sinop University, Sinop, Turkey
72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
73: Also at Texas A&M University at Qatar, Doha, Qatar
74: Also at Kyungpook National University, Daegu, Korea
75: Also at University of Hyderabad, Hyderabad, India